

SEMILEPTONIC AND LEPTONIC CHARM DECAYS AT CLEO-C

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Using e^+e^- collision data in the $\sqrt{s} \approx 4$ GeV energy region, CLEO-c has made extensive studies of semileptonic and leptonic decays of the D^0 , D^+ , and D_s^+ charmed mesons. We report recent measurements of absolute branching fractions, form factors, and decay constants that serve as precision tests of theoretical calculations.

1 Introduction

In the past decade, the arrival of CLEO-c and now BES-III has brought a wealth of new experimental data on charm physics. These pristine data samples collected at charm threshold complement the high statistics charm samples collected at B -factories and hadron colliders. This experimental renaissance is matched by the maturity of Lattice QCD (LQCD). Testing LQCD calculations of charm form factors and decay constants against measurements by CLEO-c and BES-III validates its use in other related systems, such as B decays.

The CLEO-c data samples discussed in this article were produced at the Cornell Electron Storage Ring, with e^+e^- collisions occurring at two center-of-mass energies in the charm threshold region. Here, charm mesons are pair-produced nearly at rest in the lab frame, and the particle multiplicities are $\mathcal{O}(10)$ per event. The first data sample consists of 818 pb^{-1} produced on the $\psi(3770)$ resonance, corresponding to 3.0×10^6 $D^0\bar{D}^0$ events and 2.4×10^6 D^+D^- events. The second sample consists of 600 pb^{-1} taken near $\sqrt{s} = 4170$ MeV, corresponding to 5.8×10^6 $D_s^{*\pm}D_s^\mp$ events. In the remainder of this article, sums over charge conjugate states are implied.

To reduce backgrounds, we tag one of the two D mesons in each event via full reconstruction. In this way, we infer not only the presence of a second (signal) D meson, but also its flavor and charge. At the $\psi(3770)$, D and \bar{D} are produced with no extra particles, while at $\sqrt{s} = 4170$ MeV, pairs of D_s mesons are produced with a transition γ or π^0 from the D_s^* decay. We fully reconstruct 10–15% of all D^0/D^+ decays and approximately 6% of all D_s decays.

We select electron tracks based on a multivariate discriminant that makes use of energy deposited in the electromagnetic calorimeter (compared to the track momentum), ionization energy loss of the track in the drift chamber (dE/dx), and information from the Ring Imaging Cherenkov counter (RICH). Muons are not explicitly identified; instead, we veto tracks that are associated with calorimeter deposits (*i.e.*, inconsistent with minimum-ionizing muons). We also veto charged kaons identified by dE/dx and the RICH.

One signature of semileptonic decays ($D_{(s)} \rightarrow X\ell\nu$) and leptonic decays ($D_{(s)}^+ \rightarrow \ell^+\nu$) is the presence of a weakly-interacting neutrino. We identify events containing a single neutrino by exploiting the hermeticity of the CLEO-c detector. We combine our knowledge of the e^+e^- beam parameters with a D tag and the visible candidates from the (semi)leptonic signal D decay

Table 1: $D^{0/+}$ semileptonic branching fractions (%). Uncertainties are statistical and systematic, respectively.

Mode	Tagged	Untagged	Average
$D^0 \rightarrow \pi^- e^+ \nu_e$	$0.308 \pm 0.013 \pm 0.004$	$0.299 \pm 0.011 \pm 0.008$	$0.304 \pm 0.011 \pm 0.005$
$D^+ \rightarrow \pi^0 e^+ \nu_e$	$0.379 \pm 0.027 \pm 0.023$	$0.373 \pm 0.022 \pm 0.013$	$0.378 \pm 0.020 \pm 0.012$
$D^0 \rightarrow K^- e^+ \nu_e$	$3.60 \pm 0.05 \pm 0.05$	$3.56 \pm 0.03 \pm 0.09$	$3.60 \pm 0.03 \pm 0.06$
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$8.87 \pm 0.17 \pm 0.21$	$8.53 \pm 0.13 \pm 0.23$	$8.69 \pm 0.12 \pm 0.19$

to form the missing four-momentum of the event. For signal events, the invariant mass of this four-momentum is consistent with the neutrino mass of (approximately) zero.

Absolute branching fractions are obtained by dividing signal event yields by tag yields after efficiency corrections. For leptonic decays, these branching fractions lead to a determination of the D^+ and D_s^+ decay constants f_D and f_{D_s} via

$$\Gamma(D_{(s)} \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 |V_{c\{d,s\}}|^2 f_{D_{(s)}}^2}{8\pi} m_{D_{(s)}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_{(s)}}^2}\right)^2. \quad (1)$$

For D semileptonic decays, in addition to absolute branching fractions, we also measure event yields in bins of q^2 , the square of the virtual W invariant mass. The differential decay rates obtained from these yields are related to the $D \rightarrow X$ form factors f_+^X via

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{c\{d,s\}}|^2 p_{K,\pi}^3}{24\pi^3} |f_+^X(q^2)|^2. \quad (2)$$

2 Results

2.1 Semileptonic Decays

CLEO-c results for $D^0 \rightarrow \{K^-, \pi^-\} e^+ \nu_e$ and $D^+ \rightarrow \{\bar{K}^0, \pi^0\} e^+ \nu_e$ decays are based on two complementary analyses using a 281 pb^{-1} subset of the $\psi(3770)$ dataset. The first analysis^{1,2} employs the tagging technique described in Section 1. The second analysis³ does not require a tag D and instead infers the neutrino four-momentum from the *all* the visible particles in an event. This untagged analysis attains higher efficiency than the tagged analysis, at the price of lower purity and larger systematic uncertainties. In averaging the results of these two analyses, we account for sample overlap and correlated systematic uncertainties.

Branching fractions for the D^0 and D^+ semileptonic modes are reported in Table 1. The precision of these measurements exceeds all previous results. In Figure 1, we show the measured $d\Gamma/dq^2$ distributions compared to LQCD⁴ and fitted to four models: two pole models⁵ of the form $f_+(q^2) = f_+(0)/(1 - q^2/M_{\text{pole}}^2)(1 - \alpha q^2/M_{\text{pole}}^2)$, with $\alpha = 0$ (simple) and $\alpha > 0$ (modified); and two- and three-parameter forms of the series expansion discussed in Refs.^{6,7,8,9}. All models are capable of describing the data, although the pole model fits prefer unphysical pole masses¹⁰. By taking the LQCD value of $f_+^{K,\pi}(0)$ ¹¹, we also obtain $|V_{cd}| = 0.223 \pm 0.008 \pm 0.003 \pm 0.023$ and $|V_{cs}| = 1.019 \pm 0.010 \pm 0.007 \pm 0.106$, where the uncertainties are statistical, experimental systematic, and from LQCD, respectively.

Results for D_s^+ semileptonic decays are based on 310 pb^{-1} at $\sqrt{s} = 4170 \text{ MeV}$ using a tagging technique¹². Table 2 shows first measurements of absolute D_s^+ semileptonic branching fractions and the first observations of the Cabibbo-suppressed modes ($D_s^+ \rightarrow K^{(*)0} e^+ \nu_e$) as well as $D_s^+ \rightarrow f_0(980) e^+ \nu_e$.

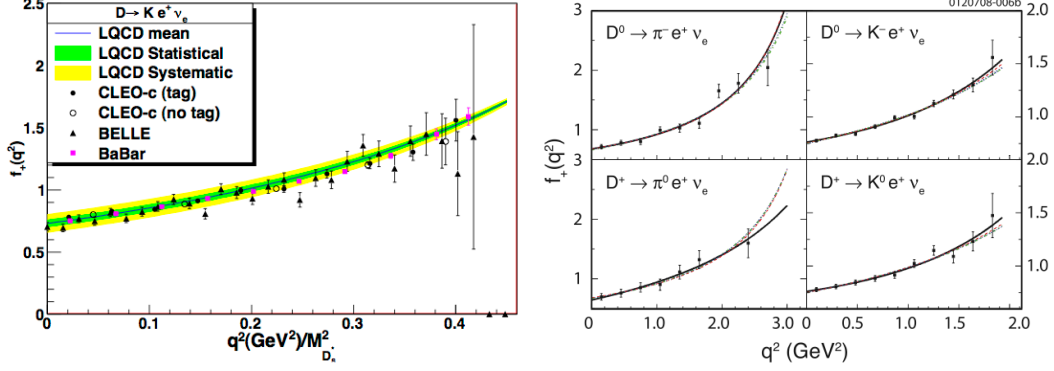


Figure 1: CLEO-c data for $f_+(q^2)$ compared to LQCD predictions (left) and fitted (right) to the simple (long dash) and modified (short dash) pole models and the two- (dot) and three-parameter (solid) series expansion.

Table 2: D_s^+ semileptonic branching fractions. Uncertainties are statistical and systematic, respectively.

Mode	$\mathcal{B}(\%)$
$D_s^+ \rightarrow \phi e^+ \nu_e$	$2.29 \pm 0.37 \pm 0.11$
$D_s^+ \rightarrow \eta e^+ \nu_e$	$2.48 \pm 0.29 \pm 0.13$
$D_s^+ \rightarrow \eta' e^+ \nu_e$	$0.91 \pm 0.33 \pm 0.05$
$D_s^+ \rightarrow K^0 e^+ \nu_e$	$0.37 \pm 0.10 \pm 0.02$
$D_s^+ \rightarrow K^{*0} e^+ \nu_e$	$0.18 \pm 0.07 \pm 0.01$
$D_s^+ \rightarrow f_0(\pi^+ \pi^-) e^+ \nu_e$	$0.13 \pm 0.04 \pm 0.01$

2.2 Leptonic Decays

Results for $D^+ \rightarrow \mu^+ \nu$ ¹³ and $D_s^+ \rightarrow \{\mu^+, \tau^+\} \nu$ ^{14,15} are based on the full CLEO-c datasets taken at the $\psi(3770)$ and $\sqrt{s} = 4170$ MeV, respectively. The decay $D^+ \rightarrow \mu^+ \nu$ is both Cabibbo-suppressed and helicity-suppressed. To search for this rare decay, we combine a tag D^- candidate with a μ^+ candidate and compute the missing (recoil) mass in the event, after discarding events with extra tracks and energy deposits in the electromagnetic calorimeter. The resultant missing-mass-squared distribution is shown in Fig. 2, and the fitted yield is 149.7 ± 12.0 events. No evidence for $D^+ \rightarrow \tau^+ \nu$ is observed. The $D^+ \rightarrow \mu^+ \nu$ yield corresponds to $\mathcal{B}(D^+ \rightarrow \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$ and $f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV. This measurement of f_D agrees well with the LQCD calculation¹¹ of $f_D = (207 \pm 4)$ MeV.

Unlike $D^+ \rightarrow \mu^+ \nu$, the decays $D_s^+ \rightarrow \mu^+ \nu$ and $D_s^+ \rightarrow \tau^+ \nu$ are Cabibbo-favored and, in the case of $D_s^+ \rightarrow \tau^+ \nu$, not helicity-suppressed. To obtain a measurement of f_{D_s} , we combine two analyses. The first analysis is sensitive to $D_s^+ \rightarrow \tau^+ \nu$, where $\tau^+ \rightarrow e^+ \nu \bar{\nu}$. We select events with a tag D_s^- candidate, a e^+ candidate, and no additional tracks. Apart from energy deposits associated with these particles, signal events contain low calorimeter activity. Fig. 2 shows the energy of unassociated calorimeter deposits, where the displacement of the signal peak from zero arises from the transition γ from the D_s^* decay. Based on the signal region below 400 MeV, we obtain a branching fraction of $\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu) = (5.30 \pm 0.47 \pm 0.22)\%$.

The second analysis is a simultaneous treatment of $D_s^+ \rightarrow \mu^+ \nu$ and $D_s^+ \rightarrow \tau^+ \nu$, where $\tau^+ \rightarrow \pi^+ \bar{\nu}$. Here, a tag D_s^- candidate is combined with a track and a photon candidate, and we compute the missing mass in the event. Extra tracks and calorimeter energy are vetoed, and events are classified according to the calorimeter energy matched to the signal track as either μ -like ($E < 300$ MeV) or π -like ($E > 300$ MeV). Missing-mass-squared distributions for both types of events are shown in Fig. 2, and we obtain branching fractions of $\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu) =$

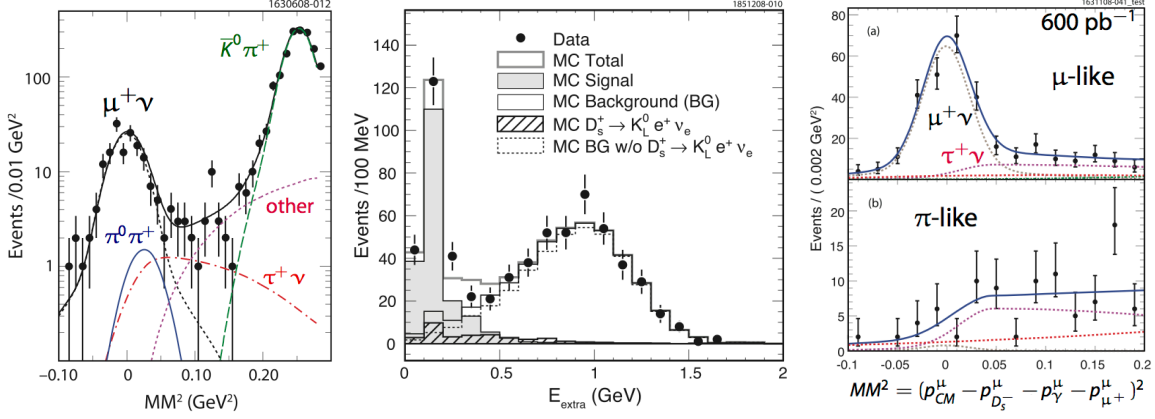


Figure 2: Missing-mass-squared distributions for $D^+ \rightarrow \mu^+ \nu$ (left) and $D_s^+ \rightarrow \mu^+ \nu / \tau^+ (\pi^+ \bar{\nu}) \nu$ (right); and unassociated calorimeter energy for $D_s^+ \rightarrow \tau^+ (e^+ \nu \bar{\nu}) \nu$ (center).

$(6.42 \pm 0.81 \pm 0.18)\%$ and $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu) = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$.

The average D_s^+ decay constant from these three branching fraction measurements is $f_{D_s} = (259.5 \pm 6.6 \pm 3.1) \text{ MeV}$, which also agrees with the LQCD calculation¹¹ of $f_{D_s} = (241 \pm 3) \text{ MeV}$. We also obtain the ratio $f_{D_s}/f_D = 1.26 \pm 0.06 \pm 0.02$, which LQCD predicts to be 1.164 ± 0.011 .

3 Summary

Data taken at charm threshold provides a unique opportunity to investigate non-perturbative QCD. CLEO-c has performed extensive studies of semileptonic and leptonic decays of D^0 , D^+ , and D_s^+ mesons. The measured form factors and decay constants agree well with new LQCD predictions, which have uncertainties of similar size to experiment.

References

1. D. Cronin-Hennessy *et al.* [CLEO Collaboration], Phys. Rev. Lett. **100**, 251802 (2008).
2. S. Dobbs *et al.* [CLEO Collaboration], Phys. Rev. D **77**, 112005 (2008).
3. J. Y. Ge *et al.* [CLEO Collaboration], arXiv:0810.3878 [hep-ex].
4. C. Aubin *et al.* [Fermilab Lattice Collaboration and MILC Collaboration and HPQCD Collab], Phys. Rev. Lett. **94**, 011601 (2005).
5. D. Becirevic and A. B. Kaidalov, Phys. Lett. B **478**, 417 (2000).
6. C. G. Boyd, B. Grinstein and R. F. Lebed, Phys. Rev. Lett. **74**, 4603 (1995); Nucl. Phys. B **461**, 493 (1996).
7. C. G. Boyd and M. J. Savage, Phys. Rev. D **56**, 303 (1997).
8. M. C. Arnesen, B. Grinstein, I. Z. Rothstein and I. W. Stewart, Phys. Rev. Lett. **95**, 071802 (2005).
9. T. Becher and R. J. Hill, Phys. Lett. B **633**, 61 (2006).
10. R. J. Hill, *In the Proceedings of 4th Flavor Physics and CP Violation Conference (FPCP 2006), Vancouver, British Columbia, Canada, 9-12 Apr 2006, pp 027.*
11. E. Follana, C. T. H. Davies, G. P. Lepage and J. Shigemitsu [HPQCD Collaboration and UKQCD Collaboration], Phys. Rev. Lett. **100**, 062002 (2008).
12. J. Yelton *et al.* [CLEO Collaboration], arXiv:0903.0601 [hep-ex].
13. B. I. Eisenstein *et al.* [CLEO Collaboration], Phys. Rev. D **78**, 052003 (2008).
14. P. U. E. Onyisi *et al.* [CLEO Collaboration], Phys. Rev. D **79**, 052002 (2009).
15. J. P. Alexander *et al.* [CLEO Collaboration], Phys. Rev. D **79**, 052001 (2009).